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PREDICTION OF THE PROTON FLUX MAGNITUDES
FROM RADIO BURST DATA

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I. INTRODUCTION

The concept of using solar flare radio spectra as advance predictors of significant proton events was proposed several years ago¹⁻³ at AFGL. The original studies defined the basic criterion (U-shaped radio spectrum) which indicates with a high degree of probability the occurrence of a proton event. Subsequent studies addressed the question of predicting the magnitude of the proton spectrum, as measured by the proton peak flux for the energy channel: $E > 10$ MeV, using time integrated radio flux-density^{4,5}, peak flux density, mean flux density and duration⁵, and flash-phase time integrated flux-density⁶. We have shown elsewhere⁷⁻⁹ that the slope of the proton spectrum can be predicted from the width of the U of the radio spectrum. During that study, we carried out an intensive analysis of the radio and proton events from 1966 to 1973, and it became clear that there were broad correlations between various features of the radio and proton spectra which might perhaps, lead to an improved prediction for the proton magnitudes.

In the present study, we have considered a variety of radio and proton variables, based on the central idea that the energy (at the source) emitted in the radio spectrum can be expected to be well correlated with the energy (at the source) carried away by the proton spectrum. The variables considered are described in section II, and the preliminary application of these variables over a limited data base indicated successive improvement in correlations. Factors which led to considerable improvement were the locational correction and the average energy parameter for the

proton spectra, and the restriction of time integration to the duration of the U-pattern for the radio spectra. Various combinations of the proton variables were then correlated to U-time integrated radio fluxes at five frequencies, and also to the frequency integrated radio fluxes as described in section III, using the entire data base 1966-73. A prediction scheme for the proton magnitudes, based on these results is given in section IV and comments for further studies and implications of this study are given in section V.

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II. CORRELATION VARIABLES

In previous studies, the commonly used proton variable has been I_{10} , the peak proton flux in the channel $E > 10$ MeV. A variety of radio variables has been tried earlier: the peak flux⁵ at a given frequency, the time integrated flux^{4,5} at a given frequency, (including the post-burst increase), or the flash phase time integrated flux⁶ at a given frequency, typically ranging from 606 to 8800 MHz.

On general physical grounds, one can expect the total energy emitted into the radio spectrum, and the total energy carried away by the protons at the source to be well correlated. Thus instead of I_{10} , the peak-flux, one should consider additional factors for the proton correlation variable, that would effectively reflect the energy content of the proton emission. The factors we have considered are discussed below. Similarly, we consider additional properties of the radio emission, to better reflect the energy content of the radio emission at the source.

Proton Factors:

1). Average Energy Factor ρ_1 . If the integral spectrum, observed near the earth, is

$$I(>E) \sim E^{-\beta}$$

it is easily shown¹⁰ that the total energy carried by protons with energy $> E_0$ is $E_0 \rho_1 I(>E_0)$,

where

$$\rho_1 = \frac{\beta}{\beta - 1}$$

is the average energy factor. Two proton events, with the same peak flux $I_{10} \equiv I(>10 \text{ MeV})$, would have different energy contents

depending on the spectral slope β . We introduce the energy factor by considering $I_{10}^{\beta_1}$ rather than I_{10} as our correlate variable.

2) Duration τ . The total energy in the proton emission clearly depends on the duration of the event. Events with the same I_{10} but different durations will have differing energy contents, roughly proportional to the time of duration τ . We introduce the duration factor by considering I_{10}^{τ} rather than I_{10} .

3) Solar Location A. Two events, which give the same proton emission at the solar source will nevertheless be perceived quite differently at the earth due to the propagational differences according to their solar longitudes. Such considerations have been used in other related studies¹¹, and we apply a solar longitudinal correction e^{3A} , where A in radians is the magnitude of the angular distance from the standard reference longitude: 57°W . We introduce the longitudinal factor by considering $I_{10}e^{3A}$ rather than I_{10} .

In the pilot phase, we examined the effect of introducing one factor at a time, for a limited data base. Typical results for correlation with the radio time integrated flux at 8800 MHz were:

variable:	I_{10}	$I_{10}^{\beta_1}$	I_{10}^{τ}	$I_{10}^{\beta_1\tau}$
correlation coefficient	0.56	0.61	0.62	0.64

The data sample was restricted to a set of neighboring West-longitudes, so as to reduce the variations due to the longitudinal factor. It was clear that introducing β_1 or τ produces some improvement, and using both factors provides a greater improvement. A similar pilot study for the longitudinal factor showed

that the improvement in correlations was quite dramatic.

Radio Factors:

1) Range of Time Integration. In earlier studies, the full range of time for a given event, including the post burst increase, if any, was used to obtain the time integrated $\bar{I}(\omega) = \int dt I(\omega, t)$. Some events, however, may be compound events, where one set of peaks (at different frequencies) is at the time of the U-shaped peak flux profile, while another set of peaks occurs much later (or earlier) and is not part of the U-phenomenon. In such cases, one should not include the contributions due to the non-U portions. We have carefully analyzed our data base and calculated the $\bar{I}(\omega)$ by restricting the range of time integrations to the bursts in the vicinity of the time of the U-event. We found this to be especially important at the two lower frequencies: 606 and 1415 MHz, as can be seen from the improvement in correlations with I_{10} indicated below.

	Range of Time Integration	
	all-time	U-only
606 MHz	0.323	0.536
1415 MHz	0.418	0.601

2) Integration over Frequencies. In addition to the time integrated $\bar{I}(\omega)$ at various frequencies, we also considered the frequency integrated fluxes $\int \bar{I}(\omega) d\omega$ over the following ranges: (i) 606-8800 MHz, since these are easily available and give a standard representation, (ii) ω_2'' to ω_3 , where ω_2'' is the frequency of the observed minimum and ω_3 is the frequency of the peak of the high frequency branch of the U. These are measures of the energy of radio emission over the corresponding frequency ranges.

III. CORRELATIONS

The correlations between the various variables proposed in the preceding section are described here. The data base used is the same set of 24 radio U-Proton events we studied earlier in another context⁹, ranging over the period 1966-73. In view of the radio absorption problems at the limb, 3 events which were $> 85^{\circ}$ E or $> 85^{\circ}$ W were omitted. Also, one event was too close to sunset and the time information necessary for radio data was not fully available. One additional event did not have observations at some of the intermediate frequencies. This left 19 events, as described in Table I, which provides the date, the location and type; I_{10} , A , ρ_1 , τ for the protons and $\bar{I}(\omega)$ for the radio data at five frequencies, from 606 to 8800 MHz.

The actual variables to be used for correlations are presented in Table II: I_{10} , $I_{10} \rho_1$, $I_{10} e^{3A}$, $I_{10} e^{3A} \rho_1$, for the proton data and $\bar{I}(\omega)$ for 5 frequencies and $\int \bar{I}(\omega) d\omega$ over two frequency ranges for the radio data. We have omitted the proton duration study, since it is an after the fact observation and cannot be prejudged in terms of making a real time prediction based on radio data. This objection does not apply to the determination of ρ_1 , since it can be predicted⁷⁻⁹ from the width (ω_3/ω_2) of the radio U-spectrum.

The correlation coefficients for the 7 radio vs. the 4 proton variables are described in Table III. From these results, we can draw the following conclusions.

(1) The location factor e^{3A} provides an improvement in almost every case. $I_{10} e^{3A}$ is better correlated than I_{10} , and

$I_{10}e^{3A} \rho_1$ is better correlated than $I_{10} \rho_1$, for every radio variable with the sole exception of the individual frequency 4995 MHz.

(2) The energy factor ρ_1 , as in $I_{10} \rho_1$, also provides an improvement over the direct I_{10} in most cases. However, the choice between $I_{10}e^{3A}$ and $I_{10}e^{3A} \rho_1$ depends on which radio variable is being used as the predictor.

(3) Amongst the various radio variables, the individual frequencies show a moderate variation; with 2695 MHz the best for $I_{10}e^{3A}$ and $I_{10}e^{3A} \rho_1$, and 4995 MHz the best for I_{10} . The lower frequencies 606 and 1415 MHz are less reliable than the higher ones, in every case.

(4) It is better however, to use a variable integrated over the frequencies, such as $\int \bar{I}(\omega) d\omega$ over 606 to 8800, since it will be less susceptible to the variations occurring at individual frequencies. Also, it will be possible to obtain such an integrated variable, even when the individual frequencies available are not the ones used in this analysis. In fact, the correlations for $I_{10}e^{3A}$ ($r=0.806$) and $I_{10}e^{3A} \rho_1$ ($r=0.798$) vs. the integrated (606-8800 MHz) radio flux are better than those for the individual frequencies.

The best fit straight line, using $y = \log (I_{10}e^{3A})$ and $x = \log (\int \bar{I}(\omega) d\omega)$ from 606 to 8800 MHz is given by

$$y = ax + b \pm \sigma \quad (1)$$

$$a = 1.7700 \quad \sigma = 0.7110$$

$$b = -0.9408$$

Taking the exponential of eq. (1) we find the predicted

$$I_{10}e^{3A} = (0.1146) \cdot (\int \bar{I}(\omega) d\omega)^{1.770} \cdot (5.14)^{\pm 1} \quad (2)$$

The best fit straight line, using $y = \log (I_{10}e^{3A} \rho_1)$ and $x = \log (\int \bar{I}(\omega) d\omega)$ from 606 to 8800 MHz is given by

$$y = ax + b \pm \sigma \quad (3)$$

$$a = 1.6548 \quad \sigma = 0.6831$$

$$b = -0.1193$$

Taking the exponential of eq. (3), we find the predicted

$$I_{10}e^{3A} \rho_1 = (0.7598) \cdot (\int \bar{I}(\omega) d\omega)^{1.6548} \cdot (4.82)^{\pm 1} \quad (4)$$

The data points and the best fit straight lines for $I_{10}e^{3A}$ and $I_{10}e^{3A} \rho_1$ vs $\int \bar{I}(\omega) d\omega$ from 606 to 8800 MHz are represented graphically in Figures 1 and 2 respectively.

TABLE I
RADIO AND PROTON DATA

Index	Date	Optical Flare	Radio Time Integrated Flux $\bar{I}_{(\omega)}$				Proton Factors					
			Type	Location	606	1415	2695	4995	8800	I_{10} (a)	A Rad	ρ_1
					MHz							
1	24Mar66	2N	N20W42	0.27	0.33	0.75	1.55	2.14	(12.24)	0.2618	2.48	72
2	28Aug66	2B	N22E05	41.7	4.20	5.74	15.8	16.2	(16.30)	1.0819	5.37	13
3	27Feb67	2N	N27E02	3.97	3.18	7.68	23.1	45.6	(3.32)	1.0296	9	150
4	23May67	3B	N28E28	2175	261	42	75	138	1036	1.4833	1.42	100
5	28May67	3B	N28W32	3.48	4.65	12.3	10.9	34.8	115	0.4363	3.58	75
6	29Sep68	2B	N17W51	0.39	0.60	2.34	5.19	5.61	31.87	0.1047	10	97
7	30Oct68	3B	S14W37	14.2	4.97	8.76	10.4	7.25	133	0.3490	1.69	35
8	26Feb69	2B	N13W46	17.5	2.20	8.37	9.83	15.6	14.4	0.1920	8	33
9	27Feb69	2B	N13W65	3.42	0.90	4.10	10.6	8.27	28.1	0.1396	7.5	23
10	21Mar69	2B	N20E17	11.3	2.76	6.17	14.2	15.8	4.74	1.2913	1.8	85
11	29Mar70	2B	N13W37	0.66	2.75	6.97	19.7	18.8	65.48	0.3490	4.75	160
12	23Jul70	1B	N09E09	20.7	7.76	1.49	4.46	9.82	11.8	1.1517	1.53	23
13	24Jan71	3B	N18W49	8.13	7.72	22.3	43.7	50.1	1171	0.1396	3.57	192
14	06Apr71	-B	S19W80	0.23	0.49	2.01	8.49	5.04	51.0	0.4014	1.90	96
15	28May72	2B	N09E30	6.74	4.12	8.81	10.6	28.8	8.72	1.5182	5.88	144
16	04Aug72	3B	N14E08	201.6	33.8	62.5	143.6	303.4	68486	1.1343	4.15	96
17	07Aug72	3B	N14W37	38.9	19.1	37.3	65.1	247.5	3534	0.3490	1.85	192
18	29Apr73	2B	N13W73	7.8	28.5	7	12	55	46.69	0.2792	5.93	192
19	03May73	2B	S14E51	0.59	1.58	2.89	3.28	5.19	2.24	1.8846	8.5	20

(a): Protons $\text{cm}^{-2} \text{ sec}^{-1} \text{ ster}^{-1}$

TABLE II
VARIABLES FOR CORRELATIONS

Index	Radio Variables			Proton Variables				
	$\bar{I}(\omega)$ in 10^{-17} Joules $m^{-2} Hz^{-1}$, at: MHz	$\int \bar{I}(\omega) d\omega$ in 10^{-14} Joules m^{-2} over: " " " "	ω_1	$I_{10} \rho_1$	$I_{10} e^{3A}$	$I_{10} e^{3A} \rho_1$		
606	1415	2695	4995	8800	606	12.24	30.4	26.8
					ω_2	16.30	87.5	418.6
					$-\omega_3$	3.32	29.9	72.9
						1036	1472	88687
1	0.27	0.33	0.75	1.55	2.14	10.6	11.6	12.24
2	41.7	4.20	5.74	15.8	16.2	110.6	98.6	16.30
3	3.97	3.18	7.68	23.1	45.6	175.9	174.5	3.32
4	2175	261	42	75	138	1719	539.8	1036
5	3.48	4.65	12.3	10.9	34.8	121.8	129	115
6	0.39	0.60	2.34	5.19	5.61	31.5	31.5	31.87
7	14.2	4.97	8.76	10.4	7.25	72.2	34.7	133
8	17.5	2.20	8.37	9.83	15.6	84.1	80.0	14.4
9	3.42	0.90	4.10	10.6	8.27	57.7	59.5	28.1
10	11.3	2.76	6.17	14.2	15.8	91.9	34.8	4.74
11	0.66	2.75	6.97	19.7	18.8	111.4	106.9	65.48
12	20.7	7.76	1.49	4.46	9.82	51.4	40.0	11.8
13	8.13	7.72	22.3	43.7	50.1	279.9	273.5	1171
14	0.23	0.49	2.01	8.49	5.04	39.7	13.7	51.0
15	6.74	4.12	8.81	10.6	28.8	110.0	105.5	8.72
16	201.6	33.8	62.5	143.6	303.4	1244	2434	68486
17	38.9	19.1	37.3	65.1	247.5	823.5	1934	3534
18	7.8	28.5	7	12	55	186.6	2413	46.69
19	0.59	1.58	2.89	3.28	5.19	26.9	1354	2.24

TABLE III
CORRELATION COEFFICIENTS

Proton Variable

Radio Variable	I_{10}	$I_{10}e^{3A}$	$I_{10}e^{3A}\rho_1$	$I_{10}\rho_1$
A. $\bar{I}(\omega)$ at:				
8800 MHz	0.718	0.758	0.773	0.727
4995 MHz	0.781	0.776	0.780	0.780
2695 MHz	0.759	0.777	0.794	0.771
1415 MHz	0.601	0.749	0.711	0.546
606 MHz	0.536	0.707	0.662	0.474
B. $\int \bar{I}(\omega) d\omega$ over:				
606-8800	0.753	0.806	0.798	0.736
$\omega_2'' - \omega_3$	0.502	0.631	0.712	0.578

TABLE IV

ρ_1 vs β			
β	ρ_1^*	β	ρ_1^{**}
5.0	1.25	1.13	7.5
4.0	1.33	1.0	8.0
3.0	1.50	0.9	8.5
2.5	1.67	0.75	9.0
2.0	2.00	0.6	10
1.8	2.25	0.5	11
1.6	2.67		
1.5	3.00		
1.4	3.50		
1.3	4.33		
1.2	6.00		
1.166	7.00		

* $\rho_1 = \frac{\beta}{\beta-1}$ in this column. $\rho_1 \rightarrow \infty$ for $\beta \rightarrow 1$. We do not use this formula for $\beta < 1.166$.

** ρ_1 , as a physical energy factor must remain finite. The slope $\beta \leq 1$ is generally valid only over a limited energy range, and then the true ρ_1 will not become infinite. We have assigned these values of ρ_1 for $\beta < 1.166$.

IV. PREDICTION SCHEME

From the correlations described in the preceding section, we can develop a real time prediction scheme for obtaining the proton flux magnitude I_{10} using radio variables and the location of the flare as input variables. From Table III, we observe that either the individual $\bar{I}(\omega)$ at 2695 or 4995 or 8800 MHz, or the integrated results $\int \bar{I}(\omega) d\omega$ from 606 to 8800 MHz can be used as the input radio variables. Out of the four predicted quantities I_{10} , $I_{10} \rho_1$, $I_{10} e^{3A}$, $I_{10} e^{3A} \rho_1$ the latter two generally have the better correlations. We will use the integrated radio variable 606-8800 MHz, since it provides the highest correlations. The 'predicted' quantities $I_{10} e^{3A}$ or $I_{10} e^{3A} \rho_1$ are given respectively by eqs. (2) or (4). To obtain I_{10} , one must multiply by e^{-3A} for eq. (2), or by $e^{-3A} \rho_1^{-1}$, for eq. (4).

The location factor A can be obtained directly from the flare position data, in real time, and that correlation is easily applied. Thus eq. (2), followed by the e^{-3A} correction, provides a reasonable scheme for the prediction of I_{10} .

The energy factor

$$\rho_1 = \frac{\beta}{\beta - 1} \quad (\beta > 1) \quad (5)$$

cannot be obtained a priori. However, our earlier studies⁹ have shown that the relation

$$\beta = \frac{1.185}{(\log_{10}(\omega_3 / \omega_2''))}^{1.01} \quad (6)$$

provides a good estimate for the proton spectral slope and, consequently for ρ_1 , through eq. (5). That equation is valid only for $\beta > 1$. Should one obtain a wide U, eq. (6) will predict

$\beta < 1$ and then one must supplement eq (5) with the following empirical relationship. In fact, such a relationship was used in studying the correlations described in the previous sections, where 5 of the events in Table I had directly measured $\beta < 1$. The ρ_1 values for these events were approximately set according to Fig. 3 or Table IV, which departs from eq. (5) for $\beta \leq 7/6$ or $\rho_1 \geq 7$. Thus eq (4), followed by the $e^{-3A} \rho_1^{-1}$ correction determined from the locational and radio data, using the procedure described above, provides another way to predict I_{10} .

We illustrate both of these procedures by a concrete example: On 30 April 1976, a 2B solar flare occurred, reaching maximum phase at 2110 UT. From the real time radio and optical data, we find:

Position: S09W47 , $A = 0.175$ Rad

$x = \int \bar{I}(\omega) d\omega$ from 606 to 8800 MHz: 64.0

$\omega_2'' = 2695$ MHz, $\omega_3 = 11641$ MHz, $\omega_3 / \omega_2'' = 4.32$.

(i) Applying eq. (2), we predict

$$I_{10} e^{3A} = (0.1146) (64.0)^{1.770} = 180.4$$

and applying the e^{-3A} correction with $A = 0.175$ provides

$$I_{10} = 106.9 \text{ cm}^{-2} \text{ sec}^{-1} \text{ ster}^{-1}.$$

(ii) Applying eq. (4), we predict

$$I_{10} e^{3A} \rho_1 = (0.7598) (64.0)^{1.6548} = 740.6$$

To determine the ρ_1 correction, we use eq. (6) which gives the prediction, $\beta = 1.87$, and from Table IV or Figure 3, $\rho_1 = 2.15$

Applying the $e^{-3A} \rho_1^{-1}$ correction to the above equation, we obtain the predicted

$$I_{10} = 204.5 \text{ cm}^{-2} \text{ sec}^{-1} \text{ ster}^{-1}$$

The actual, observed I_{10} for this event was $370.0 \text{ cm}^{-2} \text{ sec}^{-1} \text{ ster}^{-1}$. Thus both methods provide a reasonable prediction in this case, well within the standard deviation factors of (5.14), and (4.82), respectively.

V. CONCLUDING REMARKS

In this study correlating radio and proton variables, with the aim of predicting the proton flux magnitude I_{10} , we have shown that:

- (1) the time integration over the radio data should be restricted to the time of the U-only;
- (2) it is better to use an integration over a frequency range such as 606-8800 MHz rather than use $\bar{I}(\omega)$ at individual frequencies;
- (3) the locational factor e^{3A} improves the correlations;
- (4) the proton average energy factor ρ sometimes improves the correlations.

Other factors that were considered, but not fully explored, are the proton duration τ , and variations of the radio frequency range of integration such as $\omega_2'' - \omega_3$ or the full available range. It is not clear why $\omega_2'' - \omega_3$ does not work as well as 606-8800 MHz. (See Table III).

The data sample of just 19 events cannot be considered to be large enough to provide decisive answers about what the best parameters or procedures are: we can only indicate, from this limited data base, what ought to be explored further. In this sense, the central issue we have raised here is that of trying to correlate the total radio energy (for the U-time) to the total proton energy, and the improved correlations suggest that this inquiry should be pursued further over an extended period of time.

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9. P. Bakshi and W. Barron; "Prediction of Solar Flare Proton Spectral Slope from Radio Burst Data," to be submitted to *Journal of Geophys. Res.* (1978).
10. P. Bakshi and W. Barron; "Predicting Riometer Absorption for Solar Radio Bursts. I. Correlations between Proton Spectra and Riometer Absorption," AFGL-TR-76-0166, (1976).
11. See for example, E.W. Cliver "Parent Flare Emission at 2.8 GHz as a Predictor of the Peak Absorption of Polar-Cap Events", Naval Electronics Laboratory Center Report NELC/TR 2015, 1976. The prescription for this correction was developed by Smart and Shea in their proton prediction program for AFGWC.

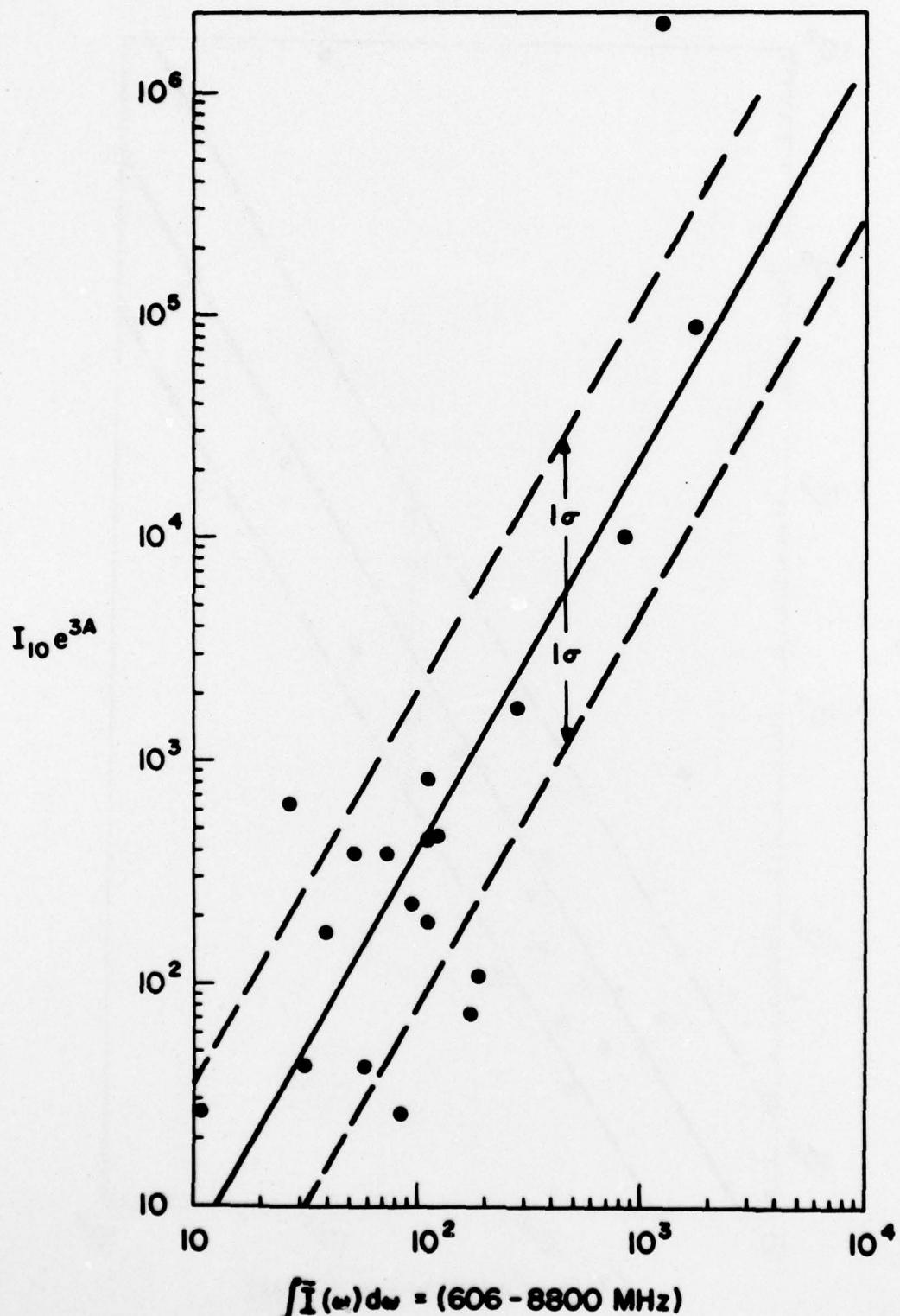


FIGURE 1.

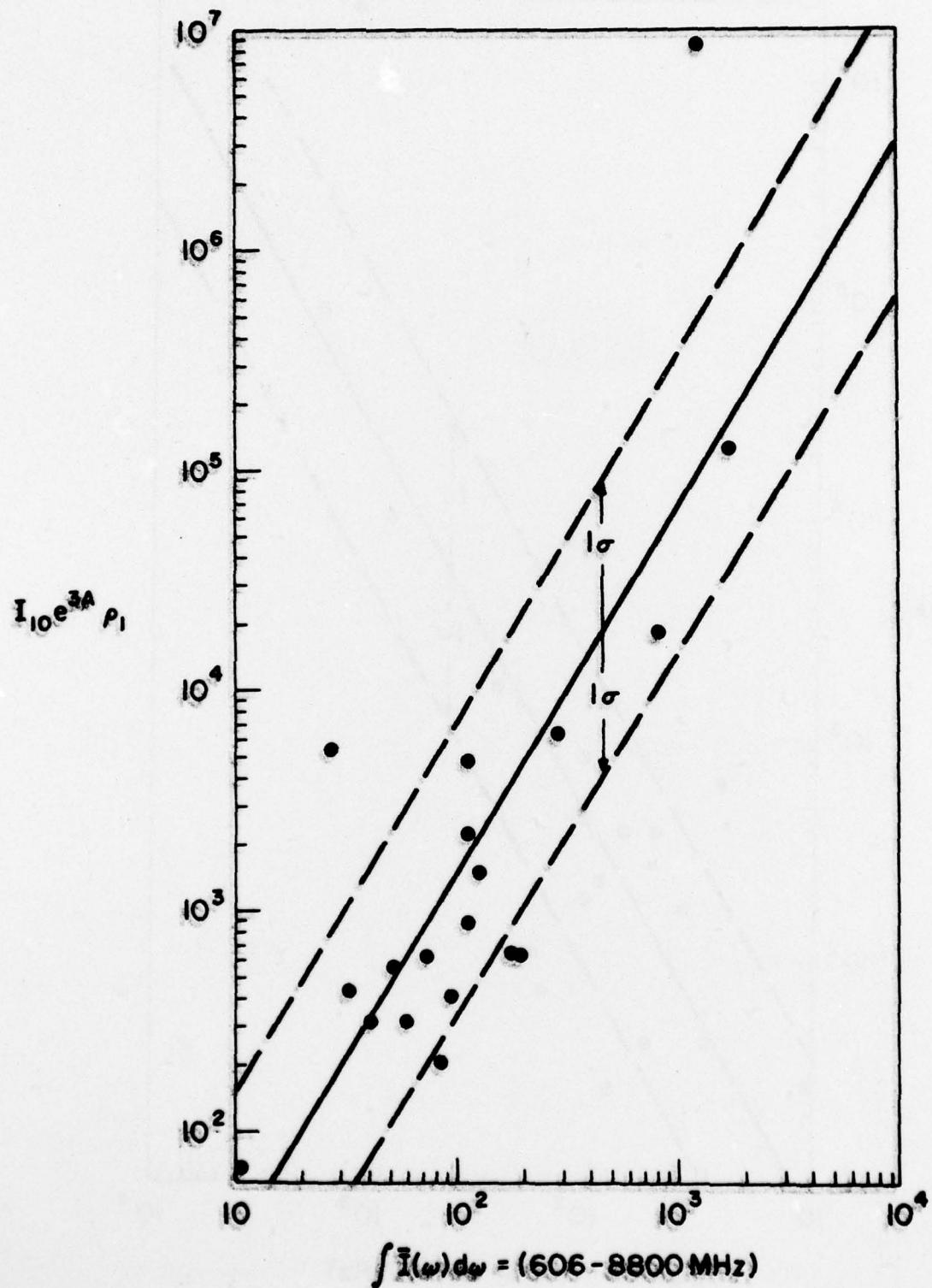


FIGURE 2.

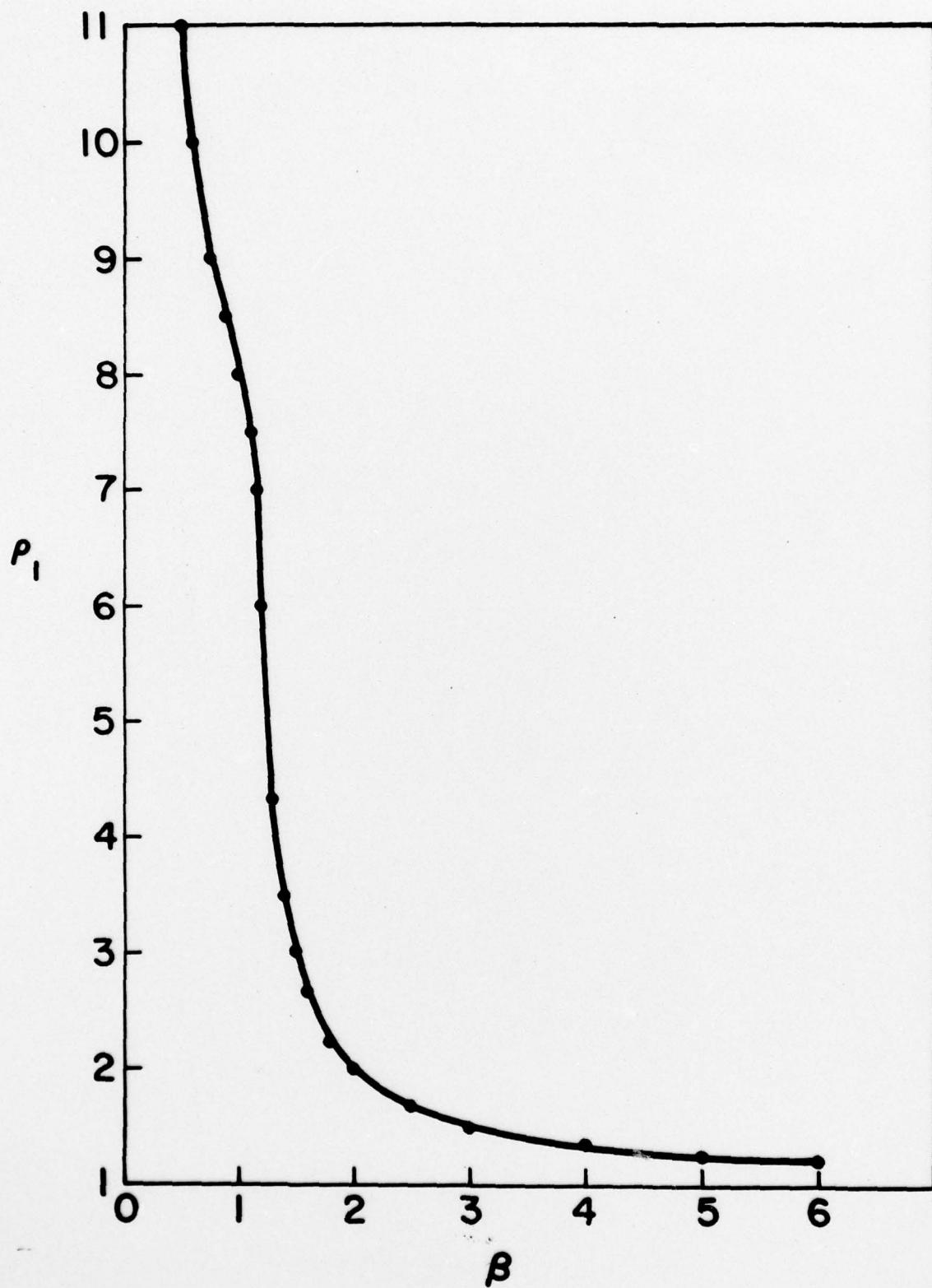


FIGURE 3.